Energy Research and Development Division
FINAL PROJECT REPORT

FIELD DEMONSTRATION OF A 2010 EPA AND CARB EMISSIONS COMPLIANT HPDI LNG TRUCK

Prepared for: California Energy Commission
Prepared by: Westport Power Inc.

Westport™

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PREFACE

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- Transportation

Field Demonstration of a 2010 CARB and EPA Emissions Compliant HPDI LNG Truck is the final report for the Certification and Field Demonstration of a 0.2g/bhp-hr NO_x HPDI LNG Truck project (contract number 500-08-043) conducted by Westport Power Inc. The information from this project contributes to Energy Research and Development Division's Transportation Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Westport Innovations is a leader in gaseous fuel engine technology. The company developed a 15-liter high pressure direct injection engine that is powered by liquefied natural gas. The goal of this project was to test the advances in clean transportation technology made through deploying heavy duty natural gas fuel vehicles that meet the California Air Resources Board and the Environmental Protection Agency 2010 emissions standards. The scope of the project included the certification and testing of the Westport High Pressure Direct Injection liquefied natural gas heavy duty engine that was based on the Cummins 15-liter ISX diesel engine to the 2010 Environmental Protection Agency and California Air Resources Board emission standards of 0.20 grams per brake horsepower-hour nitrogen oxides and 0.01 grams per brake horsepower-hour particulate matter. The engine test results were successful and led to regulatory certification approval by the Environmental Protection Agency and California Air Resources Board.

The inclusion of in-fleet field testing was utilized to accumulate on-road hours to assess the vehicle performance and to collect indicative information on fuel consumption and the diesel exhaust fluid used in the after-treatment system. The researchers concluded that the fuel consumption results calculated from the measured data were better than expected while reasonably close to that expected based on data collected in the engine test cells.

The field trial experience identified some areas where Westport could make improvements to the new system and to introduce them before significant numbers of engines were manufactured.

Keywords: Natural gas, liquefied natural gas, LNG, high pressure direct injection, HPDI engine, 15-liter heavy duty engine, class 8, commercial transportation, greenhouse gases, fuel efficiency

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EXECUTIVE SUMMARY

Introduction

Westport Power Inc. (Westport), a leader in the development and manufacture of natural gas powered engines sought to develop, certify, and test the Westport GX 15L High Pressure Direct Injection (HPDI) compression ignition natural gas engine to the emission standards set for 2010 by the California Air Resources Board (CARB) and the Environmental Protection Agency (EPA) for heavy-duty engines.

Purpose

The purpose of this project was to certify and verify the performance of the Westport GX engine to the rigorous 2010 emission standards of 0.20 grams per brake horsepower-hour (g/bhp-hr) nitrogen oxides (NO_x), 0.01g/bhp-hr of particulate matter (PM) and 0.14g/bhp-hr of non-methane hydrocarbons (NMHC). The project was related to a larger engine development project funded by the South Coast Air Quality Management District (SCAQMD) and the Long Beach and Los Angeles ports. Data on the performance and efficiency of demonstration vehicles powered by the Westport GX2010 engine were collected to verify market acceptance and correct any deficiencies. The scope of this project included the engine certification testing process and the selection and implementation of an appropriate fleet to test the engine performance in an in-fleet application.

The objectives of this project were to:

- Certify the Westport HPDI engine to the CARB and EPA 2010 emission standards for heavy-duty on-road trucks.
- Commission the engine build into the certification test facility.
- Conduct tests established with the EPA and CARB in order to certify the 2010 emissions compliant Westport HPDI engine equipped with an emissions control system.
- Prepare a report containing cold Federal Test Procedure (FTP), hot FTP and Supplemental Emissions Test (SET) composite results including certification of cold FTP NO_x, NMHC, carbon monoxide (CO) and carbon dioxide (CO_2) and hot FTP NO_x, NMHC, PM and CO_2 data.
- Demonstrate an EPA 2010 liquefied natural gas (LNG) HPDI engine used in heavy-duty class 8 truck applications though selection of a working fleet within the South Coast Air Basin.
- Ensure that the supply and infrastructure for diesel exhaust fluid (DEF) was available for the six-month field trial.
- Provide LNG truck operation training to drivers within the demonstration fleet.

- Collect field data for six months that illustrated the LNG truck performance in terms of LNG truck fuel economy, LNG truck urea consumption rate and LNG truck mileage accumulation.

Project Results

The strategy employed in executing the project was to develop the data required to confidently certify an engine to the 2010 CARB and EPA standards in-house followed by sending the engine to a third-party test facility to verify local development and testing completed at the Westport engine testing facilities. The third-party test data was submitted to CARB and EPA for their certification. Ricardo Inc's testing facilities were selected for the final certification testing of the engine to satisfy the certification requirements. The 2010 Westport GX engine was sent to Ricardo's technical center in Chicago. It was installed and commissioned into the engine test cell and the tests required to satisfy the EPA and CARB requirements were performed to collect evidence that would support engine certification.

The project team installed a 2010 representative engine into a working fleet in order to validate system performance and operation once the certification process was completed. It was necessary for the engine to be integrated with a selective catalytic reduction (SCR) system as part of the after-treatment system to comply with new emission standards. This required further integration of the SCR system onto the fleet vehicles, which did not operate 2010 ISX diesel engines with SCR systems. The SCR system required the use of diesel exhaust fluid (DEF), a urea-based chemical reactant used to reduce NO_x emissions.

The second component of the project was to conduct a truck field trial and demonstration. The goal was to locate customer fleets with operational characteristics suitable for the field trial and identify six to 10 trucks that would participate. The availability of fleets willing to take part in the demonstration was limited by the availability of deployed LNG vehicles in the market. Only one suitable fleet with three trucks was secured to take part in the trials at the time the study was commissioned. The trial fleet that operated drayage trucks in the Southern California Air Basin offered experience with varied drive cycle operation and represented a market likely to embrace the new engine, although it was not a high mileage fleet, which is the preferred example for testing.

The trucks were ordered once the project team secured an agreement with the trial fleet. Delivery of the vehicles was delayed due to a lack of availability and long procurement lead-time of critical after-treatment parts. These issues caused an initial delay in the "up-fit "process in which model year 2009 trucks with 2009 engines were upgraded with the engine and after-treatment hardware to make them representative of the 2010 system.

The demonstration project covered six months, during which information on fuel consumption, DEF, and engine performance was logged. During the demonstration there were some mechanical issues that interrupted the miles logged. This allowed for the issues to be identified and corrected. The demonstration project ended at the end of March 2011 with the three trucks logging cumulative mileage of 167,000 miles over a six-month period.

The 2010 GX engine system successfully demonstrated that it could achieve the stringent EPA and CARB emission requirements and also demonstrated sub 0.2g/bhp.hr NO_x emissions. The application to CARB and EPA was completed, which led to certification approvals from each (an Executive Order and a Certificate of Conformity, respectively).

The research team was able to verify preliminary performance of the 2010 engine and emission controls system based on the field experience resulting from operation of three trucks over the six-month trial period. Over this period the fleet customer logged miles travelled, fills of LNG, diesel, and DEF used in daily operation. The results highlighted the performance of the HPDI system in varied drive cycle operation.

The fuel consumption results of the field trial demonstrated that the performance for all three trucks was better than expected. The total diesel equivalent fuel consumption (LNG plus diesel) resulted in an average fuel consumption of 5.7 miles per gallon over the three trial trucks with DEF consumption averaging two percent of total fuelling.

The field trial accumulated valuable operational experience and identified areas where further improvements could be made to the Westport GX 2010 system.

The project team recommended that for future field trial demonstrations a greater number of demonstration vehicles would provide an opportunity for more diverse field experience and a larger sample size, which would make the data analysis results more robust.

Project Benefits

The 2010 Westport GX engine offered a low emissions engine product that was available for sale in California. Using LNG as the primary fuel the engine also offered a reduction in greenhouse gas emissions. This natural gas engine provided a Class 8 truck option that offered the same performance (power, torque, fuel economy and responsiveness) as the industry has grown to expect from diesel engine technology and the high natural gas fuel substitution offered a significant opportunity to displace diesel fuel, thus reducing California's dependence on crude oil imports.

The transportation of all goods consumed in California occurs through the use of freight trucks in some manner. A portion of the cost of all goods can be attributed to the cost of fuel. The increased deployment of natural gas engines in freight transportation will lead to lower operator costs, a greater competitive advantage for fleets, and competitive prices for consumers. Stable natural fuel prices will help grow the California economy by reducing risk.

California is the largest economy in the United States and the eighth largest in the world according to 2009 figures, with a tremendous opportunity to lead the nation in economic growth and development. The deployment of new natural gas engine technologies such as the Westport GX could lead to the expansion of the natural gas vehicle market to include vehicles in higher weight classes. Job creation opportunities in vehicle sales, maintenance, training and education, and related vehicle services could expand throughout the Southern California region and beyond. Job growth in natural gas infrastructure including compressed natural gas (CNG) and LNG production, storage and dispensing will also see correlated increases with vehicle deployment.

Promoting natural gas heavy duty engine development and demonstrations as illustrated through the deployment of the Westport GX engine will help establish California as leaders in transportation technology innovation for years to come.

CHAPTER 1:
Introduction and Project Overview

1.1 Introduction

Westport Innovations Inc. is a global leader in alternative fuel, low-emissions technologies that allow engines to operate on clean-burning fuels such as compressed natural gas (CNG), liquefied natural gas (LNG), hydrogen and biofuels such as landfill gas. Westport technologies reduce nitrogen oxides (NO_x), particulate matter (PM) and greenhouse gas (GHG) emissions while preserving the power, torque and fuel efficiencies of diesel engines.

The Westport high pressure direct injection (HPDI) technology enables diesel cycle engines to operate using natural gas while retaining the same levels of torque, horsepower and efficiencies experienced with a diesel-fuelled engine.

Westport's HPDI technology has been developed over the last ten years and has been operating in fleets since 2001.

For this project Westport sought to receive emissions certification for 2010 in order to be compliant with the stringent requirements set forth by the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB), and to demonstrate and trial the 2010 engines within a commercial fleet, which operates in Southern California, for six months to assess their performance.

The emissions standards set by the EPA for this engine type is 0.20g/bhp-hr for NO_x, 0.01 g/bhp-hr particulate matter (PM) and 0.14g/bhp-hr non-methane hydrocarbon (NMCH).

The scope of this project included the certification and testing of the GX engine in a test cell environment employing approved tests prescribed by the EPA testing protocols including cold Federal Test Procedure (FTP), hot FTP and Supplemental Emissions Test (SET) composite results.

Part two of the project included the selection of the test fleet, ensuring availability (infrastructure and supply) of the diesel exhaust fluid, operator training, field trial support and data collection.

The data collected provides a preliminary assessment of the performance of the Westport 2010 GX engine with the addition of the selective catalytic reduction (SCR) after-treatment system. The ability to test the engine within a commercial fleet, prior to launching the engine provides in-use validation and identifies any unexpected issues that may arise, thus allowing for engineering changes before the engine is released into mass production.

The funding provided by the California Energy Commission (CEC) financed the costs of completing the tasks described in this report. Other tasks relating to the development of the 2010 GX engine were funded by the South Coast Air Quality Management District.

1.2 Background and Overview

The Westport GX engine involved in this project utilizes the HPDI engine technology using the Cummins ISX 15 L diesel engine as a base engine. The HPDI engine uses diesel-cycle principles to achieve a significant substitution of diesel fuel with natural gas.

As the engine's piston approaches top-dead-center on the compression stroke, the HPDI injector injects a small quantity of "pilot" diesel fuel, which ignites spontaneously. This is immediately followed by a larger injection of natural gas, which provides 90 to 95 percent of the fuel energy; thus HPDI is commonly referred to as a "heavy-duty pilot ignition engine". The direct injected natural gas burns in a diffusion flame as it is injected and the engine operates on the thermodynamic diesel cycle.

By retaining all the operating principles of conventional diesel engines, HPDI engines retain the horsepower, torque, efficiency, and transient response of diesel engines.

The Westport GX engine is fuelled with LNG – a safe, cost effective, low carbon, and low emission fuel. LNG is stored on board the vehicle in Westport-developed LNG tanks, in capacities ranging from 70 gallons to 120 gallons, in both single and dual tank configurations. With the addition of a small volume diesel tank, 30 gallons for example, the total fuel storage capacities enabled are up to 86 diesel equivalent gallons (deg) for a single tank setup, or up to 142 deg for a twin tank setup. The trial trucks have a single 120-gallon LNG tank configuration and have a range of approximately 250 miles.

Westport's HPDI system for heavy-duty trucks utilizes LNG as the main fuel. LNG is drawn from the LNG tank and is pressurized by the tank-mounted LNG pump. Using warm engine coolant, a vaporizer (heat exchanger) warms the high-pressure LNG, changing it to high-pressure CNG. This CNG provides the primary fuel to the engine. At the same time, diesel fuel is drawn from the diesel tank to an engine-mounted, high-pressure diesel pump. This high-pressure diesel is supplied to the Fuel Conditioning Module (FCM) that controls the diesel pressure to the fuel injectors.

Inside the engine, Westport's HPDI injectors deliver small amounts of diesel fuel and sequentially a large amount of CNG into the diesel engine combustion chamber. The diesel pilot flame ignites the natural gas, which in turn provides the engine's power stroke.

Inside the cab, mounted to the dash, is a specific Driver Display for the LNG system. This Driver Display informs the driver of the system status (LNG fuel level and other system parameters) and the Gas Detection Monitor checks for and indicates any natural gas leaks in both the cab and the engine bay.

The HPDI system has been designed and developed for application with Cummins ISX 15-liter engines, and the Westport 2010 GX offers ratings of 400 hp to 475 hp and 1450 ft-lbs to 1750 ft-lbs of torque.

Certification to the 2010 standards would require the addition of a SCR system to the existing 2007-certified GX engine.

The research undertaken in this project will help advance the shift away from the exclusivity of diesel engines in the transport sector by offering fleets an alternate fuel engine options that provide the same performance and fuel efficiency they are accustomed to while providing additional benefits such as GHG reductions and fuel cost savings opportunities.

The objectives of continuing to advance technologies in natural gas engines are multifold. Firstly, the advantages of using natural gas as transportation fuel in the class 8 commercial truck market will assist in the overall reduction of GHG and assist California reach its goal to reduce carbon dioxide (CO_2) emissions Secondly, natural gas engines in high fuel use segments such as freight transport will reduce dependence and use of foreign petroleum and will reduce operating costs for commercial fleets due to lower priced fuel.

1.3 Project Objectives

The objectives of this project were to:

- Certify the HPDI engine to be compliant with the 2010 U.S. EPA emission standards, namely 0.20 g/bhp-hr NO_x, 0.01g/bph-hr PM and 0.14g/bhp-hr NMHC;
    - Ship, install and commission the EPA 2010 engine build into the certification test facility and to ensure that engine is fully operational to begin conducting tests;
    - Conduct tests as established with the U.S. EPA and CARB in order to certify the 2010 emission compliant Westport GX engine equipped with an Emission Control System;
    - Complete test reports that contain Cold FTP, Hot FTP and SET composite results that include:
        - Certification Cold FTP NO_x, NMHC, carbon monoxide (CO) and CO_2 data;
        - Hot FTP NO_x NMHC, PM and CO_2 data;
        - SET Composite NO_x NMHC, PM, CO and CO_2;
- Complete all tasks related to conducting an in-fleet demonstration project including:
    - Selection of fleets in South Coast Air Basin to participate in field demonstration;
    - Ensure infrastructure and adequate supply of urea for six month field demonstration;
    - Operator training for LNG trucks
    - Delivery of vehicles with EPA 2010 engines;
    - Deployment and ongoing customer support for field trial;
    - Collection of field trial data on LNG fuel economy, urea consumption and mileage accumulation.

1.4 Project Tasks

Project tasks for the Scope of Work covered by this research project are as follows:

Task 2.0 Certification of EPA 2010 HPDI Engine

1. Task 2.1 Engine Commission
2. Task 2.2 Engine Testing
3. Task 2.3 Test Reports

Task 3.0 Truck Field Demonstration

1. Task 3.1 Fleet Demonstration Selection
2. Task 3.2 Infrastructure and Supply for Diesel Exhaust Fluid
3. Task 3.3 LNG Truck Operation Training
4. Task 3.4 Truck Delivery
5. Task 3.5 Field Demonstration Deployment and Support
6. Task 3.6 Field Trial Data Collection

CHAPTER 2:
Task 2: Certification of EPA 2010 HPDI Engine

The Scope of Work for this project was structured into eleven (11) tasks. There were three subtasks under Task 2 and six subtasks under Task 3.

Task Group 2 of the project was focused on the tail end of the new engine development where the certification testing and reporting compiled evidence for successful product certification of the Westport GX engine to the 2010 emission standards. The introduction of the new emission standards set forth by the EPA and CARB created the need to develop and certify the Westport GX engine to the 2010 emissions standards for tailpipe emissions.

In order to meet the 2010 standard of 0.2g/bhp-hr NO_x, the technology chosen to meet the new NO_x standard was a SCR. The urea based SCR system for the Westport GX reduces the remaining engine-out NO_x to achieve the required limit. The PM is controlled with a diesel particulate filter (DPF), coupled with a diesel oxygen catalyst (DOC). In summary: Urea SCR for NO_x and DOC + DPF for PM control.

Following the addition of this equipment to the base engine, a series of prescribed tests were completed to ensure that engine-out emissions and engine performance were within acceptable parameters.

2.1 Engine Commission

Following the completion of certification testing and engine tuning at the Westport testing facility, the GX 2010 engine was shipped from Vancouver to the Ricardo Chicago Technical Center where it was installed and commissioned in the certification test cell.

Commissioning consisted of a series of measurement and operational checks to ensure that the engine and the test cell measurement equipment were operating as expected.

Commissioning was completed by Nov. 19, 2009 and the engine and test cell were deemed ready for certification development work to begin. Figure 1 shows the test cell installation at Ricardo Chicago technical center. Upon completion of the engine testing, the GX engine was shipped back to Westport facilities.

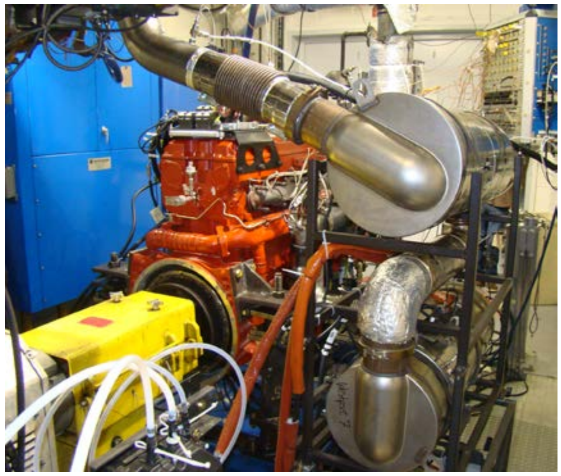

Figure 1: Certification Engine Installation

2.2 Engine Testing

Certification development testing was conducted at Ricardo Chicago Technical Center to optimize engine performance and emissions over the FTP[1] and RMCSET[2] cycles. Certification testing is an intensive effort which focuses primarily on collecting the verification data required to support a submission to the regulatory agencies. This final stretch of testing also provides the last opportunity for final adjustments to the calibration in order to achieve the best possible end result.

Equipped with an acceptable calibration, resulting from the development leading up to certification, the combustion and performance engineers conducted the certification tests agreed to by CARB and EPA using the duty cycles and procedures specified in 40 CFR §86.1333–2010, §86.1360–2007, and §86.1362–2007 [3]. Emissions of all regulated pollutants were measured as specified in 40 CFR Part 1065. Testing was also conducted to determine the emissions adjustment factors required for infrequent regeneration events as per §86.004–28.

The certification tests consisted of:

- Cold + Hot FTP
- RMCSET
- FTP Upward Adjustment Factor (UAF)
- RMCSET UAF

The testing took place in Nov- Dec, 2009 and the results met the targets required for certification submission and will be illustrated in greater detail in task 2.3.

[1] FTP = Federal Test Procedure, and relates to a transient mode of operation

[2] RMCSET = Ram Mode Cycle Supplemental Emissions Testing, and relates to steady state operation

[3] Refers to the Code of Federal Regulations (EPA), Under "Title 40", Section (§) 86.xxxx

2.3 Test Reports

The certification testing was conducted at a third party lab, thereby meeting the requirements of 40 CFR Part 1065. The emissions results in Table 1 have been reported to CARB and EPA.

Table 1: Certification Test Results

	Regulated Emissions - CVS (g/bhp-hr)			
	CO	**NOx**	***NMHC**	**PM**
Cold FTP	0.22	0.24	0.03	0.006
Hot FTP	0.01	0.09	0.02	0.001
Cold + Hot Composite FTP	0.04	0.11	0.02	0.002
Hot FTP with DPF regen	0.02	0.21	0.01	0.010
UAF	0.000	0.001	0.000	0.0001
DF	3.2	1.2	1.2	0.002
FTP inc. UAF & DF	**0.13**	**0.14**	**0.02**	**0.004**
RMCSET	0.01	0.11	0.02	0.000
RMCSET with DPF regen	0.02	0.25	0.01	0.005
UAF	0.000	0.002	0.000	0.0001
DF	3.2	1.2	1.2	0.002
RMCSET inc. UAF & DF	**0.03**	**0.13**	**0.02**	**0.002**

* Note: NMHC results are corrected for gas composition differences between tested gas and CARB gas specification

The results in Table 2 show that emission targets have been met with good compliance margin to the 2010 emission standards. In addition, brake specific fuel consumption and diesel exhaust fluid (DEF) consumption meets targets without having appreciable ammonia or nitrous oxide slip over the cycles.

Table 2: Further Results from Certification Tests

	THC (g/bhp-hr)	NH3 (g/bhp-hr)	N2O (g/bhp-hr)	CO2 (g/bhp-hr)	BSFC (g/bhp-hr)	Urea (g/bhp-hr)	NO / NO2 (ratio)
Cold FTP	1.42	0.00	0.03	490	202	2.02	1.90
Hot FTP	0.94	0.00	0.03	462	189	3.14	0.50
Cold + Hot Composite FTP	1.01	0.00	0.03	466	191	2.98	0.70
RMCSET	0.60	0.00	0.01	381	158	2.65	1.30

The SET points and not-to-exceed (NTE) control area were determined from the engine power map. Figure 2 shows the SET and NTE control area for the highest rating of the GX engine family, 475hp / 1750ft-lb.

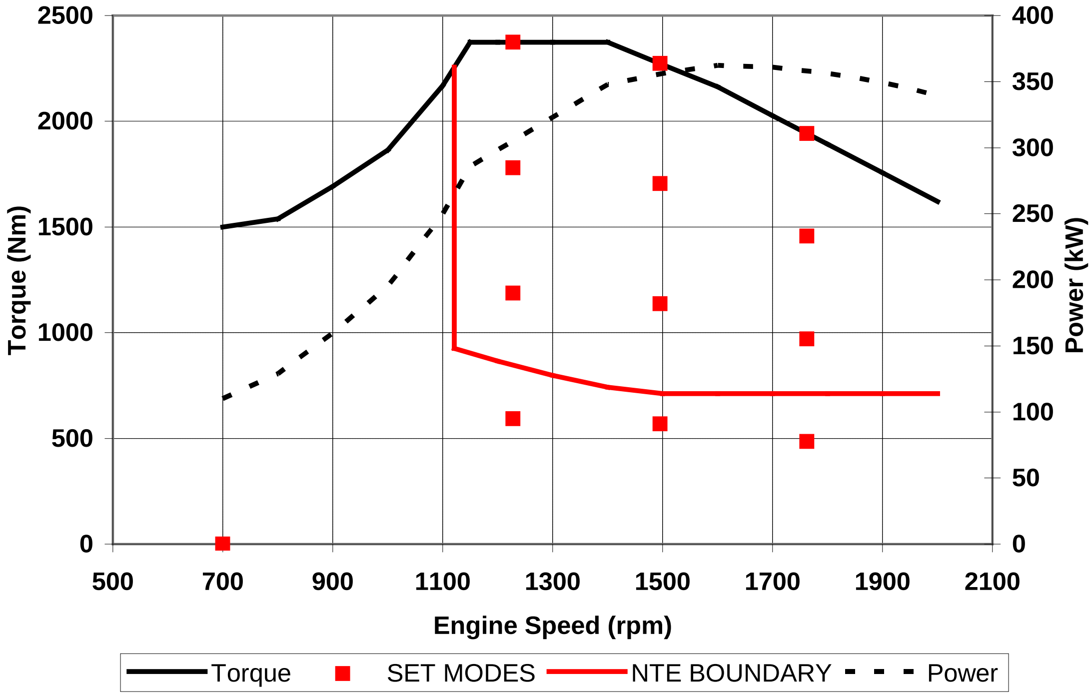

Figure 2: SET and NTE Zone for the Westport GX 475hp / 1750ft-lb Engine

For a NO_x standard of 0.2g/bhp-hr, the NTE limit is 0.3g/bhp-hr. The mapping data from the certification testing shows that the GX engine complies with the NTE NO_x requirements.

The engine is integrated with an exhaust Particulate Filter System (PFS) that is very efficient in removing PM from the exhaust stream. Engine test results over the FTP and SET tests showed that the PM emissions are in the order of 80 percent to 90 percent lower than the certification standard. Since the PFS has such high efficiency it was deemed unnecessary to conduct a PM NTE test because the only way that the standard could be exceeded would be through a PFS failure.

Following task 2.3 Westport submitted the results to the regulatory agencies for certification approval and supported the tedious process that required information to be provided based on additional requests from the agencies. One such additional request was related to the assigned values of deterioration factors (DF's). The assigned DFs that were agreed upon are recorded in Table 1.

The certificate of conformity from EPA was received June 30, 2010 and the Executive Order from CARB was received on July 6, 2010.

CHAPTER 3
Task 3: Truck Field Demonstration

Task 3 of the project tasks revolved around the demonstration phase of the project where the 2010 engine was integrated into a commercial fleet for on-road field testing. The goal of this task was to gain initial experience with the new engine providing an opportunity to identify any improvements or fixes that may be required. This trial also provides a preliminary check on in-use fuel and DEF consumption, and overall engine performance in a Class 8 heavy-duty truck application.

3.1 Fleet Demonstration Selection

The goal of this task was to select a demonstration fleet within the Southern California region that would best suit the capabilities and applications for the Westport GX engine. Originally it was expected to demonstrate the GX engine in more than one fleet for a total of 6 to 10 trucks, however, there were difficulties in finding a second fleet. This was primarily due to the limited availability of fleets in the South Coast Air Basin that were using a compatible Westport GX engine that could be upgraded to the 2010 system. Westport had offered financial incentives where possible to try to secure the participation of an additional fleet, but these attempts were unsuccessful and only one fleet was secured for the six-month demonstration project. The preferred profile of a demonstration fleet would be one that accumulated high mileage hauling higher loads such as 80,000 lbs Gross Vehicle Weight, so as to accumulate field experience with a higher duty cycle (intensity). This approach would typically be expected to be the most successful approach for identifying shortcomings where opportunities may exist for improvement.

The fleet selected for the demonstration project was California Cartage Inc. with operations for this demonstration project based out of the Ports of Long Beach. California Cartage has one of the largest drayage fleets in the United States with significant operations in Southern California, which operates logistics companies and warehouses. California Cartage has also been supportive of integrating “Green Trucks,” many of them LNG, into its fleet and agreed to the field trial of the three trucks in this demonstration project. The Cal Cartage trucks operated as port drayage trucks between the Ports of Long Beach and locations within the Southern California Basin. Although the trucks were only expected to accumulate moderate mileage, they satisfied the on-road testing requirements and provided valuable operating data and experience.

3.2 Infrastructure and Supply for Diesel Exhaust Fluid

A common industry term for a water based urea solution used with SCR is DEF. A requirement of the project was to ensure that the availability of DEF was secured for the duration of the demonstration project. It was confirmed that two local companies were capable of maintaining a supply DEF for the field trial fleets. Cummins Cal Pacific and SC Fuels (Southern Counties Oil Company) have deliverable package volumes ranging from five gallons to fifty-five gallons that would be available in stock for next day delivery. Furthermore, many fuel stations have DEF available, as well.

Packaged containers of DEF fluid were preferred for ease of re-fill measurement and simple handling logistics.

3.3 LNG Truck Operation Training

The drivers of the trucks with the upgraded 2010 engines and emission control systems were identified and enrolled in training. The training was based upon Westport's standard LNG Tractor Operating and Maintenance program with the addition of a separate module that has been updated for the 2010 engine and LNG system. Westport's Sales and Customer Care Group led the training program for the demonstration program. The training program reviewed standard operation of an LNG truck including: pre-trip inspection, starting, operational modes and failure modes, and re-fuelling and then covered the unique changes to the trucks with the new 2010 engine and emission control system. DEF re-fill requirements were reviewed and field trial tracking log-books were introduced.

3.4 Truck Delivery

Field Test agreements were signed with the trial customer, California Cartage, and the three owner operators of the fleet trucks and Westport prepared to conduct the "up-fit" of the 3 trial trucks. There was a delay, however, in the start of the demonstration project. Initially the delay stemmed from the delivery of the MY'09 LNG trucks from the truck manufacturer, but in the end the most notable impact was due to delays in part availability for the new after-treatment components required.

The field demonstration trucks were built by starting with MY'09 LNG trucks and conducting an "up-fit" on the trucks. The "up-fit" of the trucks refers to the process of replacing or adding additional components to upgrade the truck to the set of new 2010 specifications. The process began by taking the trucks out of service one at a time and then up-fitting them with the new engine and after-treatment system parts. The trucks were delivered back to the customers ready for service on May 27, 2010, August 5, 2010 and September 1, 2010. The 6-month goal for the demonstration project was met by the end of January, 2011 but given that the truck introduction had not been at the same time it was continued to the end of March to ensure reasonable diligence around the data collection from the trial trucks.

3.5 Field Demonstration Deployment and Support

The Westport Field Service team worked with Kenworth servicing dealerships to ensure maintenance and repair support was available for the demonstration customer.

3.5.1 Experience and New Issue Resolution

The first truck released to the field trial fleet, truck 271107, experienced a number of mechanical issues over the course of the field trial. In February the truck was taken out of service for repairs. A failed EGR valve was replaced after a test showed the valve to be faulty. Upon removal of the EGR valve, coolant was found so the EGR cooler was also replaced, as this is likely where coolant entered the EGR circuit. As part of the procedure for removing the EGR cooler the turbo was removed. This showed the turbo had been leaking oil into the charge air cooler so the turbo also needed to be replaced. The troubleshooting and repairs on this truck were extensive and unfortunately disrupted the operation of the truck during the field trial resulting in a month of down-time. The failure of these components was assessed and did not appear to be linked to the HPDI[4] engine operation. The component failures are believed to be base engine related and it was therefore concluded that they would have occurred whether the engine had been operated as a diesel engine.

Truck 271107 also experienced a gas rail plug leak where natural gas was escaping past an o-ring seal on the engine head. This may have contributed to a higher than expected amount of gas fuel consumed as demonstrated by the data from the fuel logs. This is a known failure mode though is very uncommon on HPDI engines and is not unique to a 2010 engine. This failure occurrence will provide input to Westport's corrective action process. If the failure is found to be reoccurring, then an assessment will be conducted and either a design change or a manufacturing improvement will result.

During the course of the demonstration project, Truck 271107, 271108 and 271106 experienced problems with hydrocarbon dosing control during DPF regenerations. The drivers reported both Check Engine and DPF lamps would come on. At this point the driver would stop and perform a stationary DPF regen (Diesel Particulate Filter regeneration, conducted by increasing the temperature to burn off soot accumulation). In most cases this would turn the warning lamps off but they would return within a week or two. Data logs of stationary regenerations performed in the shop by Westport service personnel showed low regeneration temperature in the DPF. This led to slow regeneration rates and most likely led to incomplete regeneration while the truck was in mobile operation.

The hydrocarbon doser calibration was further analyzed and it was established that there was an area where improvement was required to determine the right quantity of dosing to achieve the regeneration temperatures required. The dosing variables were recalibrated and it was verified that this improvement enabled more robust DPF regeneration. This gave the three field trial trucks much better temperature control during the mobile and stationary DPF regenerations and is believed to have solved the issue. Following verification, the resulting improved dosing calibration was introduced to production, thus eliminating a problem that would have otherwise been experienced by other customers as well.

[4] HPDI – High Pressure Direct Injection, of natural gas with diesel pilot ignition.

3.5.2 Ride-Along Observations

In order to obtain a better understanding of the operation of the trucks, an engineer visited the field during the field trials in the early fall of 2010 and in the spring of 2011 to conduct ride-along tours with customers in normal day to day operation. Key observations made during these trips involved:

- Fuelling and fluid re-fill practices
- General truck route and operation
- Problems with morning engine start-up

The Westport engineer observed that the re-fill procedure for putting LNG into a tank is fairly consistent. All of the Westport LNG trucks running in the Los Angeles area get a full fill each time they visit the station. At the main LNG station near the Long Beach port, the tanks are filled by a Clean Energy technician.

Fills of the diesel and DEF tanks were not observed. The driver of one truck explained that his diesel fills are always done to the same level in the tank. DEF tank fills are done with small bottles of DEF, so the level of the fill is inconsistent. However, over the course of six months the level of fills averages to a consistent tank level. This will have eliminated most of the variability errors experienced in the usage calculations.

All three trucks are hauling full containers from the pick-up site in Boron, CA to the Port of Long Beach. The trucks then return to the pick-up site with an empty container from the Port with a stop along the route at night. The drive is divided evenly between straight highway through the hills northeast of the city and freeway driving through Los Angeles in traffic. There is also a long period of engine idle while the trucks wait in the Port. This drive cycle displayed a wide variety of drive cycle operation and thus was a good testing scenario for the system.

All three drivers experienced an engine start-up issue in the morning when the engine was cold. The engine had trouble starting and ran rough, sometimes stalling. Westport discovered this was a problem with low gas system pressure that caused incorrect fuelling under specific conditions. Once the gas system pressure increased the issue would resolve itself. This issue was typically only experienced once a day. The latest engine software release by Westport solved this issue and incidents with morning starting have been resolved.

The primary intent of the field trial was to accumulate experience and collect operational data, which can be used to identify areas where further improvements can be made to the Westport GX 2010 system. The benefit of conducting trials has been demonstrated, having now completed the intended trial duration. Although there have been some challenges with the data around fuel and fluid consumption, this was to be expected given the environment in which the data was collected. The data and results included partial fills and varied truck operation, and have been influenced by some of the issues that have in turn provided valuable feedback for system improvement.

3.6 Field Trial Data Collection

Each month a data sheet was collected from each field trial truck operator, which contained mileage and re-filling events for LNG, diesel, and DEF. The data was used to enable fuel and fluid consumption analysis.

3.6.1 Mileage Accumulation

All three field trial trucks were in service for the intended 6-month trial period. As of March 31, 2011, the mileage completed as a Westport GX 2010 (EPA 2010) configured truck for each of the 3 field trial units is listed in Table 3.

Table 3: Accumulated Mileage

Truck VIN	**Accumulated Miles**
Truck 271107	*58,200 miles*
Truck 271108	*59,000 miles*
Truck 271106	*49,600 miles*

The graph in Figure 3 shows the accumulation of the mileage of each of the three (3) demonstration trucks as well as the cumulative total for the duration of the project.

Total mileage accumulated was 167,000 miles over the course of the demonstration project.

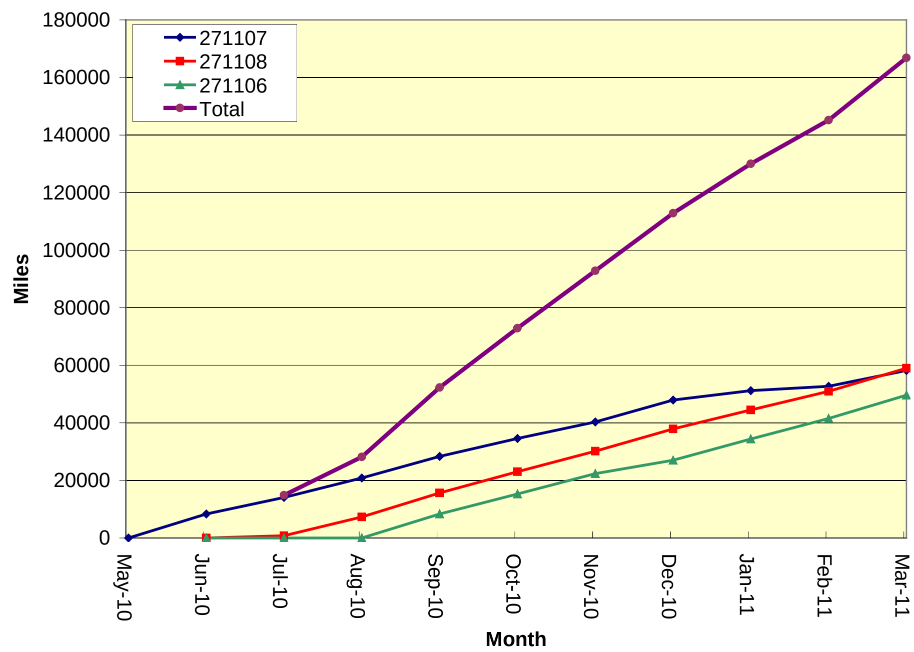

Figure 3: Cumulative Miles Per Month for Each Truck and Total

3.6.2 Fuel and DEF Economy

The operators of all three field trial trucks logged fills of the LNG, Diesel and Diesel Exhaust Fluid (DEF) tanks. For comparison to diesel-only fuelled trucks, the LNG and diesel consumed are converted on an energy basis to a total "diesel equivalent" (dsl-eq) fuel consumption. The LNG fuel is measured at the pump by mass. As per the information given by Clean Energy at the station, one diesel gallon equivalent is equal to 6.31 pounds of LNG.

LNG, diesel and DEF consumption numbers are given in Table 4 for all three trucks.

Table 4: Cumulative Fuel Consumption Analysis of GX2010 Field Trial Trucks

	271107	*271108*	*271106*	*Ave.*
Total Dsl-eq Fuel Consumption (Dsl-eq LNG + Diesel)	5.59 *MPG*	5.72 *MPG*	5.87 *MPG*	5.7 MPG
% diesel of total dsl-eq fuel consumption	12.4 %	13.0 %	11.7 %	12.4 %
% DEF gallons to total dsl-eq fuel gallons	2.4 %	2.0 %	1.6 %	2.0 %

Graphs of diesel equivalent (natural gas + diesel) fuel consumption and Diesel Exhaust Fluid over the months of the field trial are shown in Figure 4 and Figure 5, respectively.

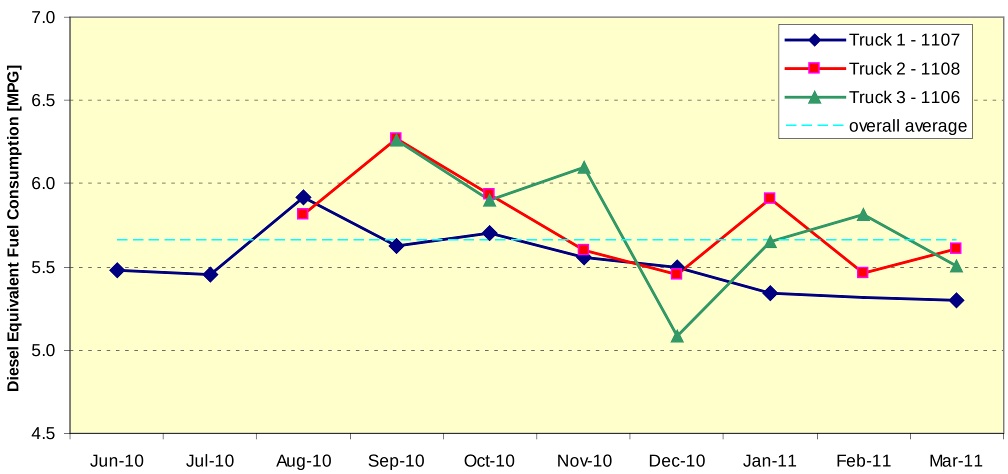

Figure 4: Monthly Diesel Equivalent Fuel Usage Data – GX 2010 Field Trial

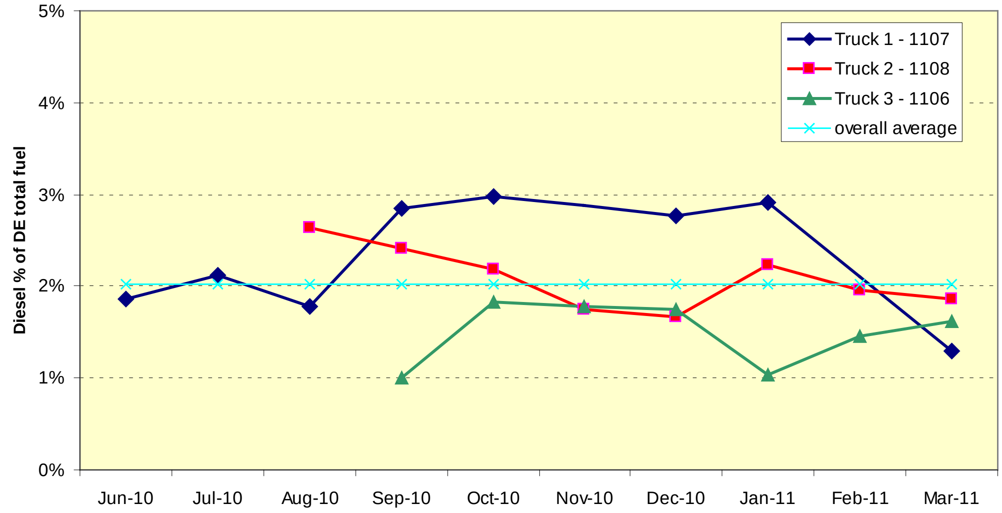

Figure 5: Monthly Relative % Diesel Exhaust Fluid Usage Data – GX 2010 Field Trial

The consumption numbers recorded on all three trucks were slightly outside of the range expected from data recorded in the engine test cell at Westport or previous field experience. Based on interpolation from drive cycle analysis representing the field trial trucks and using test cell data it was expected that the field trial trucks would get approximately 5.1 mpg with 8 percent diesel consumption (of total equivalent fuel consumption) and 1.7 percent DEF consumption relative to total equivalent fuel consumption. The slightly better than expected fuel economy may be a factor in the proportion of diesel and DEF being slightly higher than expected. While the results calculated from the three truck field trial are within acceptable range of the predicted values it is difficult to obtain a precise degree of accuracy with a small sample size in a less controlled environment. This challenge is typical of a field trial and as such for more accurate reporting it is recommended that fuel consumption tests are best conducted in a controlled test environment.

The percentage of diesel as part of the total diesel equivalent fuel consumption was calculated to be an average of 12.5 percent, however, based on test cell data (measured in a controlled test environment), this is higher than the predicted 8 percent. In considering potential sources of variation of the relative percentage of diesel fuel consumption it could have been caused by one of the following factors:

- Incorrect fuel metering at the LNG station;
- Inconsistent fill levels or recording on DEF and diesel tanks;
- Possibility of unusual drive cycles with excessive amounts of idle time;
- Mechanical issues causing each truck to use unusual amounts of LNG, Diesel, or DEF.

Investigation into the fuel metering at the station showed that it was a direct mass measurement with a constant conversion factor as described above. This is the most accurate method of measurement and thus it is not considered to be a likely factor in the calculation inaccuracy;

however, it is unknown how often the meter calibration was checked. It is difficult to assess the DEF and diesel fill accuracy, however the fill practice is fairly straight forward and the records appeared to indicate diligence. A notably greater amount of idle time could result in a higher proportion of diesel consumption given the way that the diesel and natural gas fuelling operates. More idling, however, should also result in greater fuel consumption which was not seen to be the case. No mechanical issues were detected, and this possibility seems very unlikely to be present on multiple trucks. This analysis indicates that the test results calculated from the field trial should be within reasonable accuracy. These results are specific to the field trial trucks and the way that they were operated. Trucks with different duty cycles would be expected to have different fluid and fuel consumption results.

CHAPTER 4: Summary, Recommendations and Benefits

4.1 Summary

In November, 2009 a 2010 GX engine complete with after-treatment and control system was prepared for certification testing and was shipped, installed, and commissioned in a third party test facility. Before the year was out the engine had successfully demonstrated that it could achieve the stringent EPA and CARB emission requirements and had demonstrated sub 0.2g/bhp.hr NO_x.

Final submission values were established with deterioration factors and an upward adjustment factor and the NOx NTE (not to exceed) emission area was determined and the results were confirmed to be acceptable. The application submission to CARB and EPA was completed, summarizing test results and the many other application requirements to satisfy the certification submission which led to certification approvals (Executive Order and Certificate of Conformity).

Based on the field experience resulting from operation of three trucks over the six month trial period, the Westport team was able to verify preliminary performance of the 2010 engine and emission controls system. Over this period the fleet customer logged miles travelled, fills of LNG, diesel, and DEF used in daily operation. Although the application of the trucks in the selected fleet were not involved in high mileage highway driven applications, the results served to highlight the performance of the HPDI system in varied drive cycle operation.

The fuel consumption results of the field trial demonstrated that the performance for all three trucks was better than expected based on the test cell data at Westport while being sufficiently close to be considered reasonable. The total diesel equivalent fuel consumption (LNG + diesel) resulted in an average fuel consumption of 5.7 miles per gallon over the three trial trucks with DEF consumption averaging 2 percent of total fuelling.

The field trial accumulated valuable operational experience and identified areas where further improvements could be made to the Westport GX 2010 system.

4.2 Recommendations

For future field trial demonstrations it is recommended that a greater number of demonstration vehicles would provide an opportunity for more diverse field experience and a larger sample size which would help with the robustness of the data analysis results.

4.3 Benefits to California

The 2010 Westport GX engine offers a low emissions engine product that is available for sale in California. Using LNG as the primary fuel the engine also offers a reduction in Greenhouse Gas production. This natural gas engine provides a Class 8 truck option that offers the same performance (power, torque, fuel economy and responsiveness) as the industry has grown to expect from diesel engine technology and the high natural gas fuel substitution offers a significant opportunity to displace diesel fuel thus reducing California's dependence on crude oil imports.

The transportation of all goods consumed in California occurs through the use of freight trucks in some manner. A portion of the cost of all goods can be attributed to the cost of fuel. The increased deployment of natural gas engines in freight transportation will lead to lower operator costs, a greater competitive advantage for fleets, and competitive prices for consumers. Stable natural fuel prices will help grow the California economy by reducing risk.

California is the largest economy in the United States and the eighth largest in the world according to 2009 figures, with a tremendous opportunity to lead the nation in economic growth and development. The deployment of new natural gas engine technologies such as the Westport GX, will lead to the expansion of the natural gas vehicle market to include vehicles in higher weight classes. Job creation opportunities in vehicle sales, maintenance, training and education, and related vehicle services will expand throughout the Southern California region and beyond. Job growth in natural gas infrastructure including CNG and LNG production, storage and dispensing will also see correlated increases with vehicle deployment.

Promoting natural gas heavy duty engine development and demonstrations as illustrated through the deployment of the Westport GX engine, establishes Californians for years to come, as leaders in transportation technology innovation.